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TNO report

Experimental Resin Flow Investigation for Vacuum Infusion

Contract order number F61775-02-WE044

Date	13 January 2003
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Copy no	1
No. of copies	3
Number of pages	25
Number of appendices	~
Sponsor	European Office of Aerospace Research and Development, Air Force Office of Scientific Research Laboratory
Project name	Experimental Resin Flow Investigation for Vacuum Infusion
Project number	007.62465.01.01

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
16-01-2003	Final Report	6 July 2002 - 06-Dec-02

4. TITLE AND SUBTITLE

Vacuum infusion of low-cost aerospace composites

5a. CONTRACT NUMBER
F61775-02-WE044

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Mr. Maarten Labordus

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Delft 2629 HS
The Netherlands

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0014

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SPC 02-4044

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking TNO Industrie as follows: A mold system will be designed in which the hydrostatic pressure can be measured in the resin during the vacuum infusion process. Pressure transducers will be mounted in the surface of a flat aluminum plate, and data will be digitally recorded. Simple compression tests on dry and impregnated laminate will provide data to relate the pressure gradient (out of plane) to the local laminate thickness. From a combination of the pressure data and the compression data, the correction factor on Darcy's Law can empirically be determined. Outputs of the research will be: 1. Empirical quantification of pressure gradient during vacuum infusion and Resin Transfer Molding (RTM); 2. Correction of Darcy's Law; 3. Practical test to measure compressibility of reinforcements and translation of data into above-mentioned correction term.

15. SUBJECT TERMS
EOARD, Materials, Composites, Polymers, Materials Process Design

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18, NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Charles H. Ward, Lt Col, USAF
UNCLAS	UNCLAS	UNCLAS	UL	25	19b. TELEPHONE NUMBER *(Include area code)* +44 (0)20 7514 3154

Declarations

This material is based upon work supported by the European Office of Aerospace Research and Development, Air Force Office of Scientific Research Laboratory, under Contract No. F61775-02-WE044

Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the European Office of Aerospace Research and Development, Air Force of Scientific Research, Air Force Research Laboratory

The Contractor, TNO Industrie, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract Number No. F61775-02-WE044 is complete, accurate, and complies with all requirements of the contract.

I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract.

Date: 16-01-2003 Delft.

Name and Title of Authorised Official: G.v.d. Weijde

Contents

1 Introduction

Resin Transfer Moulding (RTM) processes are characterised by a fibre preform laid-up in a closed mould system and a pressure difference to drive the resin in the mould cavity. Traditional RTM, which uses high pressures at the resin inlet to inject the resin, has been successfully applied in the aerospace industry and in the automotive industry. RTM can result in high quality composite parts, however there are many drawbacks, such as high costs for tooling and the inflexibility of the process with respect to (minor) design changes.

The vacuum infusion process, a low-cost RTM variant, was developed especially for the boat building industry . Instead of two solid mould halves and high pressures, one single solid mould halve is used, combined with an airtight flexible film and vacuum pressures to force the resin to flow. This vacuum infusion process was originally introduced as a sound alternative for open-mould processes like spray-up and hand lay-up. Besides the intended environmental and health benefits, a considerable quality improvement was noticed. Specifically, the fibre volume content was increased and the void content decreased. This led to the assumption that the vacuum infusion process could be developed into a low-cost alternative for both the RTM and the prepregging process.

Figure 1 illustrates the vacuum infusion principle and the basic equipment. The dry reinforcement is placed on a mould and is subsequently covered with a flexible foil, which is sealed at the edges leaving room for the resin inlet and outlet. During infusion the resin flows from inlet, through the fibre reinforcement and subsequently the outlet.

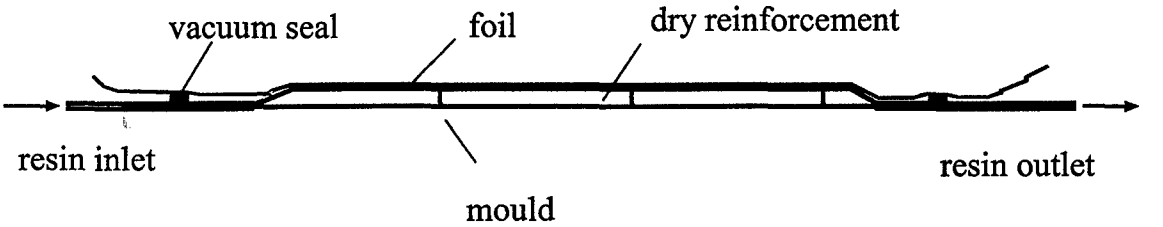

Figure 1: Schematic overview of vacuum infusion process

An important aspect of both RTM and vacuum infusion is the injection strategy. An injection strategy should be developed for each product in order to establish that the part may be filled within a reasonable cycle time (e.g. within the geltime of the resin) and that all risk of air enclosures is eliminated. Resin flow simulation software tools have been available for many years and have proven to be a useful tool to validate injection strategies. The parameters involved can be related by Darcy's Law, which serves as the basis for all resin flow simulation software. However, the underlying models used in these software tools are all based on resin flow in a stiff mould system (so on the RTM process) whereas for the vacuum infusion process the resin flow is influenced by the flexible mould halve.

In order to get a better understanding of the resin flow during the vacuum infusion process, an experimental research program was initiated, during which vacuum infusion tests were performed on different types of reinforcement materials and different lay-ups. The test set-up was designed to provide a complete overview of the resin flow parameters. This reports presents background information on the vacuum infusion process, interesting focus points for experimental research and the development of a complete test set-up. The results from the tests are presented and related to existing vacuum infusion theories.

2 Introduction to resin flow

The mathematical analysis of resin flow through a fibre preform is based on the theory of (viscous) flow through porous media, which was formulated by Darcy. Darcy's Law, combined with the continuity equation of two-dimensional incompressible flow and the appropriate boundary conditions form the basis of resin flow simulation. Applied to a one-dimensional flow, Darcy's law is:

$$Q = -\frac{KA}{\mu}\frac{\Delta p}{\Delta x} \tag{1}$$

Where
Q = volumetric flow rate [m^3/s]
μ = the fluid viscosity [Pa·s]
A = the cross section area [m^2];
$\Delta p/\Delta x$ = the pressure gradient in the flowing resin [Pa/m]
K = the reinforcement permeability [m^2]

From Darcy's law we can conclude the following about the basic behaviour of the resin flow:

- The larger the pressure difference, the quicker the part is filled;
- The lower the resin viscosity, the quicker the part is filled;
- The higher the permeability, the quicker the part is filled.

The first two parameters, pressure difference over the mould and resin viscosity, may be considered constant during infusion of the product and can be approached similarly to the ordinary RTM process. However, it is obvious that for vacuum infusion the maximum achievable pressure difference is about 1000 mbar. Related to this relatively small pressure difference (compared to ordinary RTM), low viscosity resin systems have been developed to enhance the flow rate and subsequently reduce the fill time.

The permeability is a geometrical property of the reinforcement, which describes the ease of flow through the material. The permeability can be determined from experiments, but can also be predicted by the Kozeny-Carman model. The model relates the permeability to the porosity, but in case of fibrous media, the fibre volume fraction is used.

$$K = \frac{1}{C \cdot S^2}\frac{(1-V_f)^3}{V_f^{\,2}} \tag{2}$$

Where
K = permeability [m^2]
C = Kozeny constant
S = specific surface area [m^2/m^3]
V_f = fibre volume fraction

With vacuum infusion, a solid mould halve is combined with a flexible film to close the mould. Due to the vacuum applied to force the resin through the reinforcement, the reinforcement itself is also compressed. Due to this compression, the fibre volume fraction is increased and thus the permeability of the reinforcement is decreased. A decrease in permeability in its turn alters the pressure gradient and subsequently the resin flow. Simulation software does usually not take into account the influence of the compression of the reinforcement and its related effects. Neglecting these effects introduces errors in the resin flow simulation. For critical production processes (complicated 3D products or infusion with short resin geltimes) this can lead to incorrect judgements.

3 Review of vacuum infusion research

The vacuum infusion process is a promising manufacturing concept for multiple applications. This has been recognised by the boat building industry, automotive industry and recently by the aerospace industry. This has resulted in several patented manufacturing processes based on similar concepts. The first patent dates back to 1950 with the production method called the Marco Process. A complete overview of the historical development of the vacuum infusion process is presented by C.D. Williams et al. [1]. A useful and extensive general overview of the vacuum infusion process (cost comparison, process applications, basic resin flow theory, injection strategy) is provided by Hoebergen and Holmberg [2].

More fundamental research on the vacuum infusion process focuses on the one thing that distinguishes vacuum infusion from the other RTM processes: the flexible mould halve. This flexible mould halve influences the production process by permitting compaction of the reinforcement and, thus, causing non-constant permeability. These influences on the production process also affect the product itself. In comparison with solid moulding RTM, the thickness of the product is not simply given by the dimensions of the mould cavity; it is also dependent on the compressibility and relaxation of the reinforcement under pressure.

3.1 Compaction of the reinforcement

Experiments have been performed on dry fabric to understand the compaction and relaxation behaviour. Many different models have emerged from these experiments. An example of experimental work on this subject is given by Robitaille et al. [3]. The representation of the compaction and relaxation of the fabric is based on the following relations:

$$V_f = A \cdot P^B \tag{3}$$

$$\frac{P}{P_0} = 1 - C \cdot t^{(1/D)} \tag{4}$$

Where

V_f = fibre volume fraction
P = compaction pressure [N/m^2]
P_0 = initially applied pressure [N/m^2]
t = time [s]
A = fibre volume fraction for a pressure equal to 1 Pa.
B = compaction stiffening index (B<1)
C = pressure decay after 1 sec.
D = relaxation index

The compaction of the reinforcement can also be expressed in the form of the thickness or the porosity of the laminate. The results of the experiments presented by Robitaille are all expressed in terms of the indices A through D. Comparison of the results for different testing parameters led to some general trends. For example: as the number of layers increases, the initial fibre volume fraction (A) increases while the stiffening

index (B) decreases for both random mats and woven rovings. Subsequent research [4] also focused on the compaction and relaxation of reinforcement material in fluid-saturated condition. In general, the most pronounced effects on the compaction and relaxation of fibrous reinforcements are found to be, respectively, the number of cycles and the compaction rate. The lubrication of the reinforcement seems to have the greatest influence on the time-dependent relaxation.

The aforementioned experimental work was performed on a specially designed test set-up using compacting pressures up to 1.0 MPa and compaction speeds up to 1 m/min. These high pressures and high speeds are only approachable when using a solid mould RTM process. However, the relations described above are also found to be viable for the lower pressure range (0-0.1 MPa), which is used for the vacuum infusion process. Power law relations are used in a number of vacuum infusion research programmes to model the compaction of the reinforcement material, e.g. Hammami et al. [5] and Ragondet et al. [6].

An extensive description of the compaction behaviour of a number of reinforcement materials under vacuum infusion conditions is given by Hammami [7]. In comparison to the experiments described above, the compaction pressure does not exceed 1 bar and the compaction rate is much lower (max. 2 mm/min). Figure 2 gives an example of compaction test data for a specific fibrous reinforcement material. The graph shows the typical exponential relation between the applied pressure and the fibre volume fraction, which reaches its maximum around 0.55. Also, differences are noticeable for the dry or wet situation and different compaction rates (which vary from 0.05 mm/min to 2.0 mm/min).

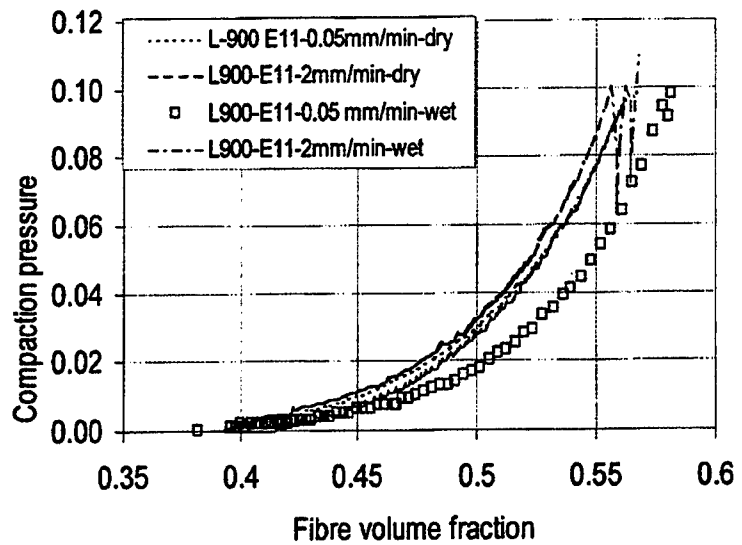

Figure 2: Reinforcement compaction test data (taken from [7]) for a 884gr/m2 0°/90° fabric from Devold

Hammami describes compaction results for various reinforcement materials, and also for preforms with flow enhancement layers. Each material with or without flow enhancement layers has its own distinct behaviour. However, in the presence of a flow enhancement layer the compaction behaviour seems to be dictated by this layer (NB. in the experiments only Rovicore and Multimat were evaluated). In accordance with the

experiments conducted by Robitaille, the compression of the reinforcement is highly affected by the compaction rate.

During the infusion process the compaction is executed in neither a saturated nor a dry situation. Rather, it is a combined process, since the dry preform is compressed first by the applied vacuum and subsequently wetted by the passing resin flow front. The resin normally causes a relaxation of the fibre preform and therefore a change in fibre volume fraction. Hammami suggests a continuous monitoring of the thickness of the laminate and pressure within the mould cavity to study this interaction.

Experimental research on compaction of the reinforcement during actual infusion has previously been presented by C.D. Williams et al. [8]. The results illustrate an interaction between the pressure, the lubrication effect and resin flow velocity. The results of the research are used to predict the thickness of fibrous preforms but are not yet related by a theoretical analysis.

3.2 Permeability

Directly related to compaction is the permeability of the reinforcement material. As mentioned in section 2, the permeability provides an indication of the relative ease of flow through porous media and can be represented by the Kozeny-Carman relation (2). As the fibre volume fraction increases as a result of compaction of the fibre preform, the permeability decreases.

Within the framework of resin flow simulation, the permeability of the reinforcement materials is an essential parameter. It serves as input for every resin flow calculation. Thus, much effort has been put into the prediction and measurement of the permeability of fibrous materials. An example of permeability measurements is presented by Labordus and Verheus [9]. In this research permeability values are determined for various reinforcement materials, including permeability values for sheared fabrics and different lay-ups. During the experiments, the pressure difference and the resin flow through a preform (compressed up to a certain fibre volume fraction) are measured and subsequently substituted in Darcy's Law to calculate the permeability. For some of the laminates the permeability of the constituent layers is determined separately to verify the rule of mixtures, which is used to predict the average permeability of a laminate. The rule of mixtures is given by the following relation:

$$K_a = \frac{1}{H}\sum_{i=1}^{n} h_i K_i \tag{5}$$

Where

K_a = average permeability for entire lay-up [m^2]
K_i = permeability of the constituent layers [m^2]
h_i = thickness of the constituent layers [m]
H = total thickness of lay-up [m]

The rule of mixtures is found to be an adequate tool to estimate the permeability for relatively thin laminates with moderately varying permeability's. However, this model does not take into account the transverse flow (flow through the thickness), which is more likely to occur for laminates with large differences in in-plane permeability.

3.3 Resin flow analysis

The governing equations for resin flow analysis are Darcy's equation (1) and the continuity equation. Simultaneous solution of the differential equations with the correct boundary conditions leads to a prediction of the flow. Herein, Darcy's equation is rewritten with the local flux density ($u=Q/A$) ('superficial velocity').

$$u_i = \frac{K_{ij}}{\mu}\frac{\partial p}{\partial x_j}$$
$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (6)$$

The actual flowfront velocity, v, can be derived by dividing the superficial velocity by the porosity:

$$v = \frac{u}{\phi} \qquad (7)$$

For a rectangular strip with length L, injected along the edge with a constant pressure difference Δp, the filling time (t_{fill}) and flowfront position ($x(t)$) can simply be derived through integration of differential equation (6), in combination with relation (7):

$$t_{fill} = \frac{\phi \cdot \mu}{K}\frac{L^2}{\Delta p} \qquad (8)$$

$$x(t) = \sqrt{\frac{2K \cdot \Delta p}{\phi \cdot \mu} \cdot t} \qquad (9)$$

A similar exercise can be performed for point injection of a circular section. The filling time for a constant injection pressure is given by the following relations (Gebart et al. [10] present the deduction of the analytical relation):

$$t_{fill} = \frac{\mu \cdot R_0^{\,2}}{2K \cdot P_i}\left\{-\ln\left(\frac{R_i}{R_0}\right) - \frac{1}{2}\left(1 - \left[\frac{R_i}{R_0}\right]^2\right)\right\} \qquad (10)$$

Where R_i and R_0 are, respectively, the radius of the injection hole and the outer radius, and P_i is the injection pressure.

With these analytical relationships, estimates of filling times can be made for simple products. The relationships are also used to verify numerical results generated with mould filling software. The software uses Darcy's law on small elements and integrates the results to obtain filling times for complex products. A description of the numerical method together with a comparison between analytical and numerical results is

presented for the RTM-Worx package by Koorevaar [11]. It shows that the difference for a circular disc between the results is not larger than 1%.

Resin flow simulation software appears to rapidly and accurately predict the flow of resin. This is certainly true for RTM processes with an entire stiff mould. However, for vacuum infusion process the resin flow does not fit the boundary conditions governing the RTM situation. In recent research programmes the effects of the flexible mould halve are acknowledged, resulting in several theoretical solutions.

An example of research that incorporates the deformation of the vacuum bag in a theoretical model is presented by Ragondet et al. [6]. The difference for the vacuum infusion model proposed in this research lie variable height of the control volume, which result in a different continuity equation:

$$\frac{\partial h}{\partial t} = -\frac{du}{dx} \cdot h \tag{11}$$

Where h is the height (thickness) of the laminate. Due the variable height, the permeability is not a constant value in the system. A combination of an empirical power law, as described in section 3.1 to model the porosity or fibre volume fraction, and the Kozeny-Carman equation (2) is used to model the variable permeability.

4 Subjects for experimental investigation

According to the theory and experimental data described in previous sections, use of a flexible mould halve during vacuum infusion clearly influences the resin flow. However, to what extent the resin flow is influenced and through which interacting phenomena is not sufficiently understood. In order to be able to perform accurate flow simulations on vacuum infused parts, it is therefore important to study and quantify all flow parameters during the vacuum infusion process. Below a short description is given of the subjects that will be addressed during this research.

4.1 Comparison vacuum infusion with RTM

To illustrate the difference between the ordinary RTM process with two solid mould halves and vacuum infusion, a comparison is made between the two processes. Using a spacer and a glass plate as top mould halve, the test set-up can be transformed and used as a completely solid RTM mould. Therefore the resin flow for both processes can be compared under similar conditions (equal pressure difference, equal product dimensions). The thickness of the laminate in the solid mould will be equal to the thickness of the vacuum infusion laminate in front of the flow front under an absolute pressure of 100 mbar. During the tests, the resin flow front and the absolute pressure in the mould will be monitored.

4.2 Pressure gradient in laminate during vacuum infusion

The resin flow during vacuum infusion is mainly dependent on the prevailing pressure gradient. The pressure gradient itself is dependent on the available pressure difference over the mould, the length of the product, but also on the local permeability of the reinforcement material. In order to obtain reliable predictions of the resin flow, a complete understanding of this pressure gradient is required.

During the experimental tests, the absolute pressure within the mould will be constantly measured using multiple pressure transducers, connected to a data acquisition system.

4.3 Compaction of the reinforcement

The non-constant compaction of the reinforcement material under the flexible mould halve is what distinguishes vacuum infusion from the solid mould RTM variants. As described in section 3.1 the compaction (and relaxation) of reinforcement material has been subject of investigation during many previous research programmes, however the tests are usually performed in a separate test set-up in either dry or saturated situations. During the proposed experiments, the compaction will be measured during actual resin flow within the mould. Therefore the effect of wetting of the fibres and resin flow velocity will be taken into account.

The compaction of the reinforcement material is measured by a number of displacement transducers placed on top of the flexible bagging film at the same location of the pressure transducers.

4.4 Effect of flow enhancement material on flow and pressure gradient

Due to the relative low pressure difference to force the resin through the reinforcement material, flow enhancement material is usually required to fill the whole mould cavity. The most common method is to add a layer of flow material on top of the laminate. Modelling of this enhanced flow is done by recalculation of the permeability of the total laminate through applying a 'rule of mixtures'. However, compared to a situation without flow enhancement material, the flow has changed from a parallel flow, to a combined parallel (through flow enhancement material) and transverse flow (through laminate). The influence of the combined flow on the compaction of the laminate and development of the pressure gradient will be investigated through measurements of the pressure- and displacement transducers. Also the influence of a sudden change in permeability, due to a drop off of the flow enhancement material will be subject of investigation.

5 Description of test set-up and procedure

The vacuum infusion tests will be performed on the test set-up schematically shown in figure 1. It consists of pressure and displacement transducers and a rectangular 10 mm thick aluminium tooling plate in which connection to the resin supply and the vacuum pump are mounted. A strip of resin distribution material is placed over the resin inlet to ensure an even distribution of the resin over the width of the laminate. The laminate, with or without flow enhancement material is laid in between the resin inlet and vacuum connection. The laminate is covered up with a flexible bagging film, which is sealed at the edges with tape.

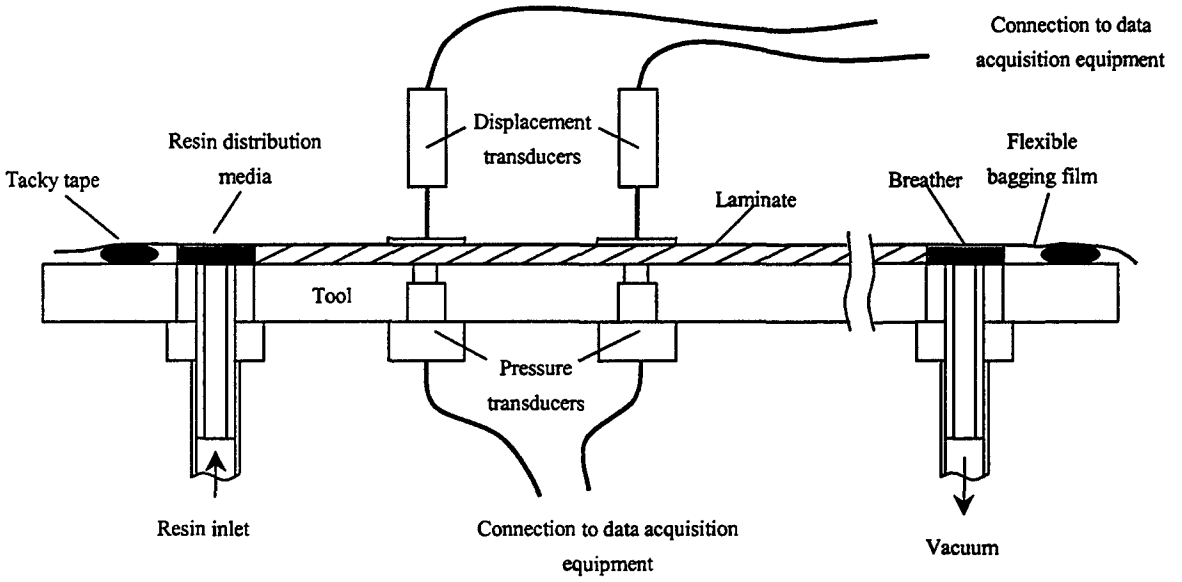

Figure 3: Schematic layout of test set-up

The laminate area has the dimensions 1800 x 200 mm. Along this length of the tooling plate holes are drilled to accommodate the pressure transducers. The pressure transducers measure the absolute pressure within the mould cavity. An excess number of holes are available in the tooling plate to facilitate variation of location and number of the pressure transducers if desired. The arms of the displacement transducers rest on top of the bagging film to measure the compaction of the laminate during infusion. The displacement transducers are held in position by a moveable holding frame.

5.1 Test procedure

Before each test run, the pressure and displacement transducers are calibrated to ensure a correct measurement of the respective quantities. In case of the displacement transducers, the tip of the measurement device is placed on the dry tooling plate and the digital display on the computer is zeroed. The pressure transducers show slight variations in the measurements depending on the location of the transducer in the tooling plate. This is probably caused by the high sensitivity of the transducers and small inaccuracies in the hole diameters in the tooling plate. To ensure a correct pressure measurement, test pressures are applied and compared to the indicated values.

If needed, a correction to the conversion formula is made. Figure 4 illustrates the calibration procedure where a special tool, connected to a vacuum pump, is used to supply the required pressures.

Figure 4: Calibration of pressure transducer

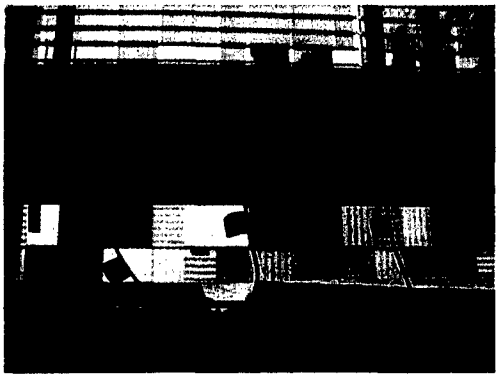

Figure 5: Bottom view of pressure transducers

Once the transducers are calibrated, the fibre mats, resin distribution media, and vacuum bag are placed on the tooling plate. The bag is sealed to the tooling plate, vacuum is applied to the system and possible leaks are repaired. Figure 6 shows a detail of the test set-up with the pressure transducers fitted in the tooling plate on the bottom and the displacement transducer resting on top of the vacuum bag.

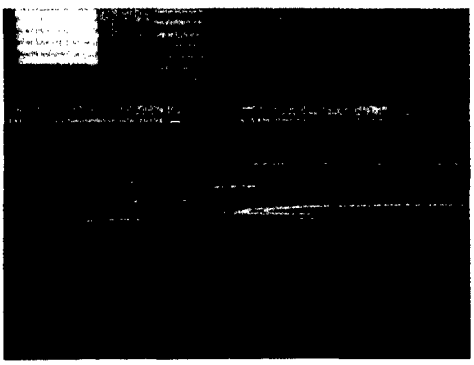

Figure 6: Pressure and displacement transducers

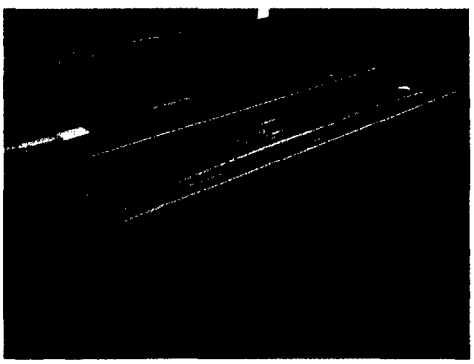

Figure 7: Overview of test set-up

To start the test, a certain pressure is applied to the system (e.g. 100 mbar), the data acquisitioning program is started, a valve is opened and the fluid will subsequently flow through the laminate. To prevent pollution of the test system glycerol is used during the tests, with a viscosity and specific weight representative for typical vacuum infusion resins. After the tests the glycerol is cleaned from the set-up. During the tests both the pressure transducers and the displacement transducer measure continuously. The data is acquired and stored in a datafile. Additionally a video camera is used to track the flowfront. Afterwards the time of the video and data recording are synchronised to determine the exact location of the flowfront during the tests.

5.2 Test Equipment specifications

Pressure transducers
The pressure transducers are miniature, flush membrane transducers from GSsensors, type: XPM10, range 2 bar, sensitivity 100 mV F.S.

Displacement transducers
Hewlett Packard DCDT displacement transducers, +/- 0.1 inch stroke range, full scale output: 1.5 VDC, 6 VDC nominal excitation

Data-acquisition system
National Instruments SCB-68 Pin shielded connector block, NI-DAQ 6.9 data acquisition card and Labview virtual instrument software.

6 Results

The results presented in this report are drawn from a first set of tests conducted on the new test set-up as presented in previous section. The results therefore serve both as demonstration of functioning of the test system as well as a first mapping of the dictating parameters of the vacuum infusion process. The materials used during the tests are glycerol, as substitution for actual resin, and Unifilo fibre mats. The Unfilo fibre mats are random oriented fibre mats, often used in marine applications with the vacuum infusion process. The Unifilo mats show large compressibility and therefore demonstrate better the influence, if any, of the deformation of the laminate under the flexible vacuum bag during infusion.

Figure 8 illustrates the development of the pressure in time at five different locations during infusion. It shows the complete cycle, from filling to constant flow and closure of the system. The test involved the impregnation of a rectangular laminate of a length of 1 metre. The respective locations of the pressure transducers are 60, 180, 300, 600 and 900 mm, measured from the resin inlet. In the figure the different lines represent the pressure readings of the transducers. As the flowfront passes the pressure transducers the readings indicate a sudden increase. The pressure rises until the mould is completely filled and a static situation is formed (the flat lines). After the static situation, the inlet valve is closed (t = 300 s), resulting in a gradual drop of the pressure as the system returns to the initial value under the influence of the applied vacuum.

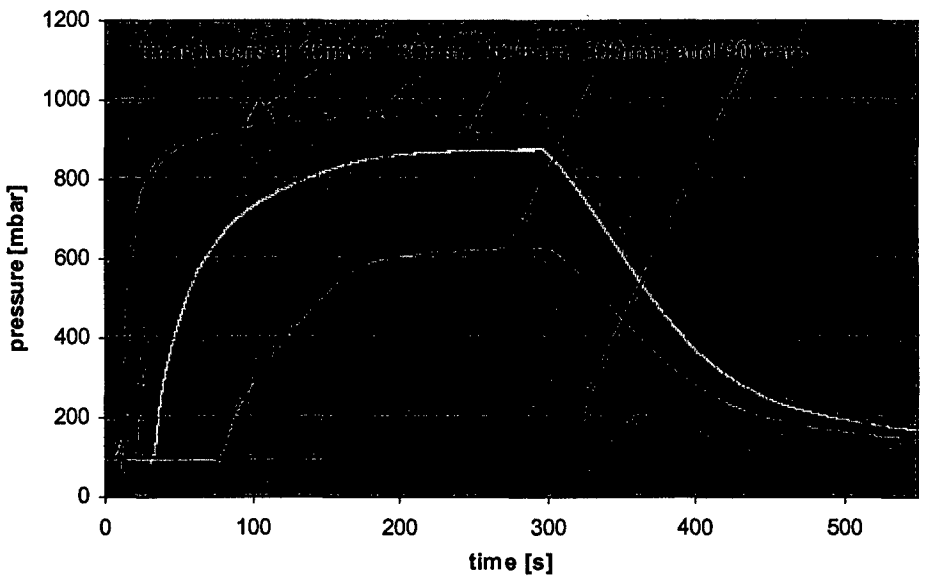

Figure 8: Pressure readings

The pressure development as described above can roughly be predicted by Darcy's law, given the correct permeability of the fibres and viscosity of the resin. However Darcy's law is deduced from a situation with an entire solid mould. To see in more detail what happens when the resin enters the mould, the deformation of the flexible mould halve is monitored by the displacement transducer. Figure 9 shows the reading of the displacement transducer, which was located at x = 180 mm. It clearly shows that a considerable deformation occurs after the flowfront has passed. The data indicate a 38%

increase in laminate thickness. Due to this relaxation of the impregnated fibres, the permeability of the laminate increases, which leads to an ease of the resin flow and therefore possibly to unpredicted resin flow and different fill times of the product.

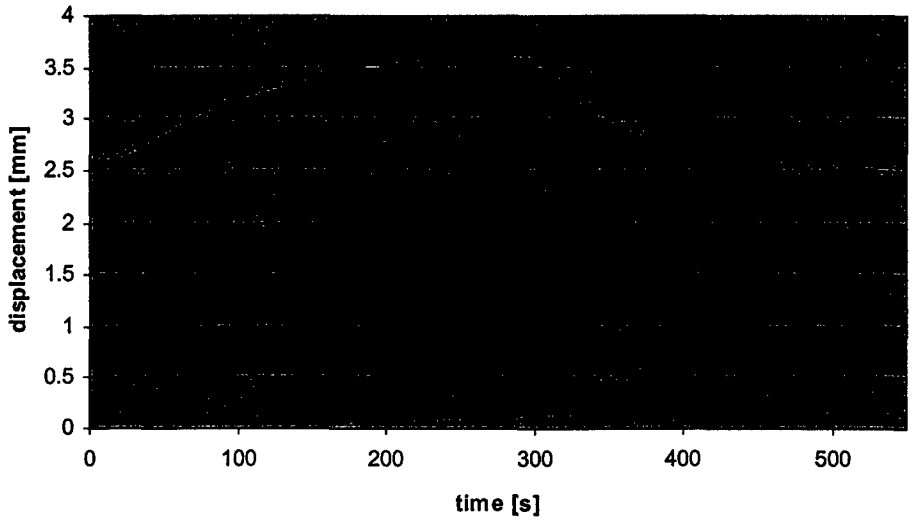

Figure 9: Displacement reading

For RTM modelling the pressure gradient over the impregnated part of the product is thought to be constant. The filling time and the flowfront position relation, as described in section 3.3 are based on this assumption. Figure 10 shows the pressure distribution over the laminate at the moment the entire mould is filled and thus all pressure transducers are overflown with glycerol. The pressure measurements are indicated by the dots in the figure, the straight line is the pressure distribution for RTM in a solid mould.

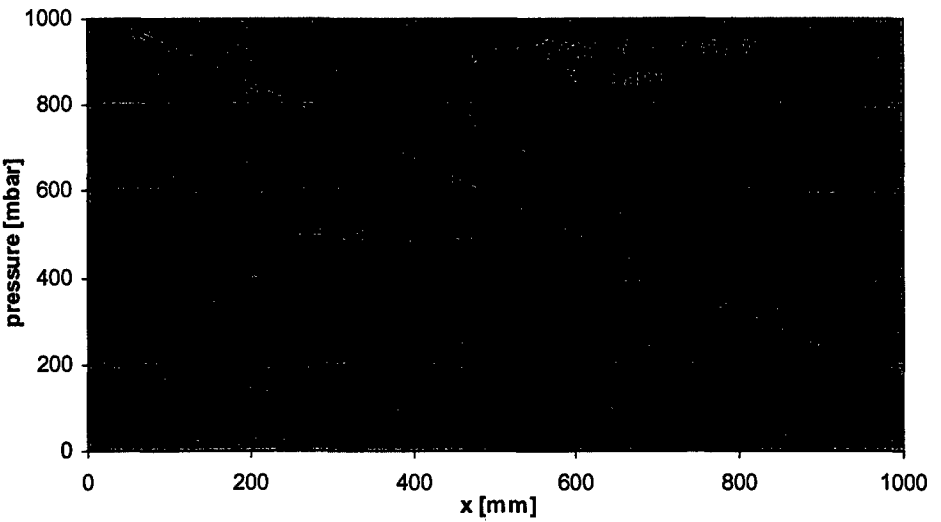

Figure 10: Pressure distribution over impregnated laminate

The pressure distribution clearly shows the difference between the vacuum infusion and 'normal' RTM process. The difference in pressure distribution is directly related to the compressibility properties of the fibre material, as predicted also by the theoretical

model of Ragondet et al. [6]. It must be stated that the results, as presented here, are acquired for fibre material with high compressibility properties, and therefore the effects are probably magnified compared to other fibre-resin systems. The pressure data is fitted with a second order polynomial. The question is if the pressure distribution as presented in figure 10 is generic for the fibre-resin system regardless of the dimensions of the impregnated laminate.

During the tests, the flowfront is monitored by a video camera. When the digital images are linked to the other data, the position of the flowfront with respect to the transducers can be determined. This procedure allows the researcher to acquire a detailed picture of the pressure development at distinct points in the product. Figure 11 illustrates the results for the same pressure data as presented in figure 8. It shows the development of absolute pressure after the flowfront has passed respectively the transducer at 60, 180 and 300 mm. From top to bottom the lines represent respectively the first, the second and the third transducer.

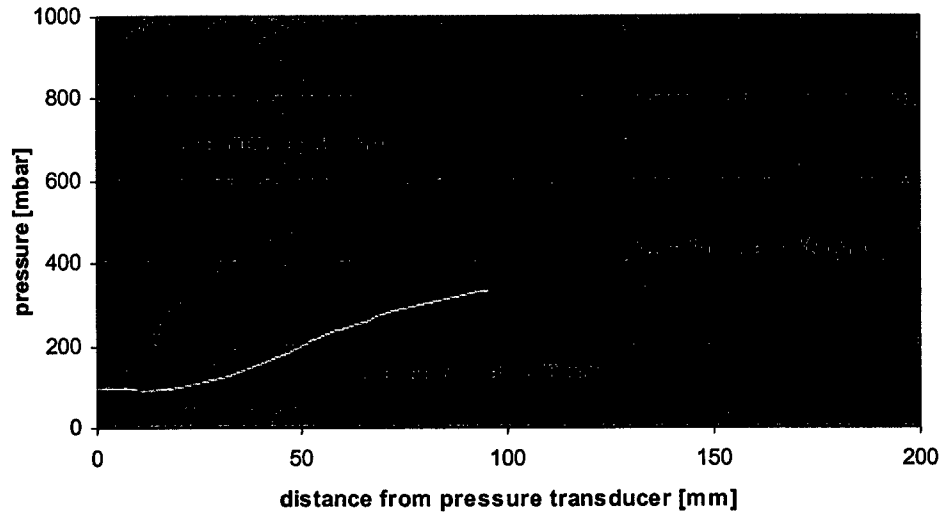

Figure 11: Pressure distributions at different locations in laminate

The figure shows, first, that the pressure development is nonlinear and therefore that the pressure gradient is nonlinear, a result expected based on Figure 10. Secondly it shows that the pressure build up after the flowfront reaches a transducer is different for each location in the product, where the pressure gradient decreases with increasing distance from the inlet. When the position data is normalised by dividing the position data by the distance from the inlet for each transducer, the results as given in figure 12 are generated. Although a large difference in number of data points obtained from each transducer makes comparison difficult, Figure 12 shows that the pressure development is similar regardless of the location in the laminate.

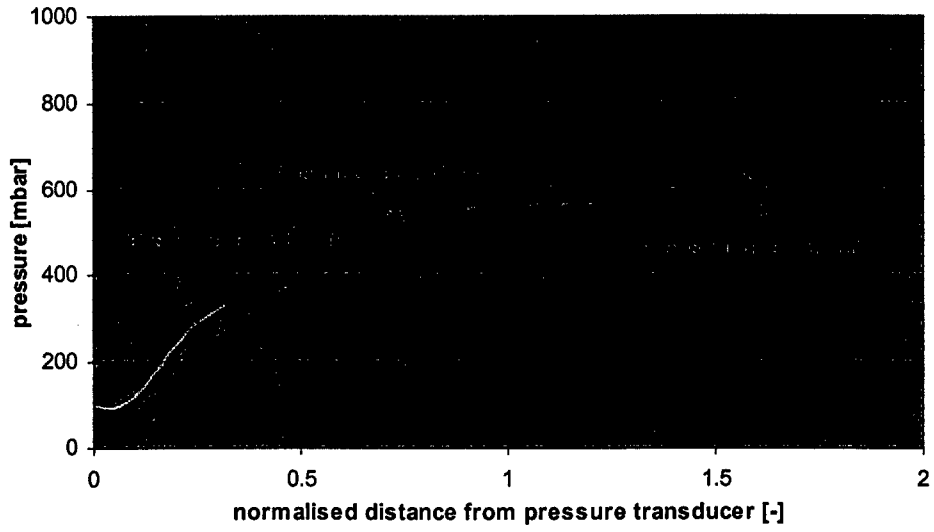

Figure 12: Normalised pressure distributions

Figure 13 illustrates a comparison of pressure distributions for two tests with different product lengths, but with equal material. The blue dots in the figure represent pressure data for a product length of 1 metre, whereas the purple squares represent data for a product length of 300 mm. The similarity between the two pressure distributions is evident. These results indicate that for given fibre material, resin system and pressure difference (Δp), the pressure distribution over the product could be regarded as a distinctive property.

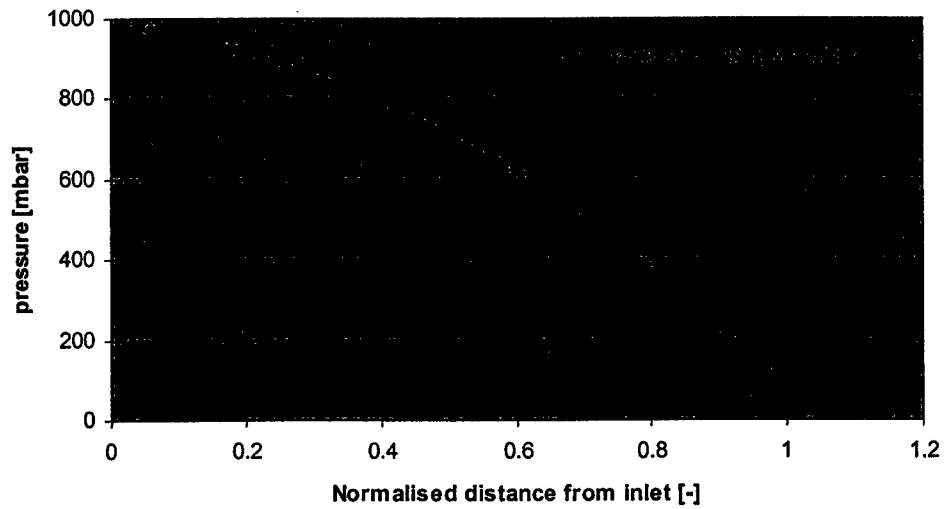

Figure 13: Pressure distribution comparison.

The test set-up will also be very useful to investigate the different options for closing an infusion experiment. Basically, four options are available:

1. close inlet channel and leave outlet channel open,
2. leave inlet channel open and close outlet channel,
3. leave inlet and outlet channel open,
4. close both inlet and outlet channel.

The resulting pressure gradients are shown in Figure 14 for a RTM set-up (linear pressure gradients).

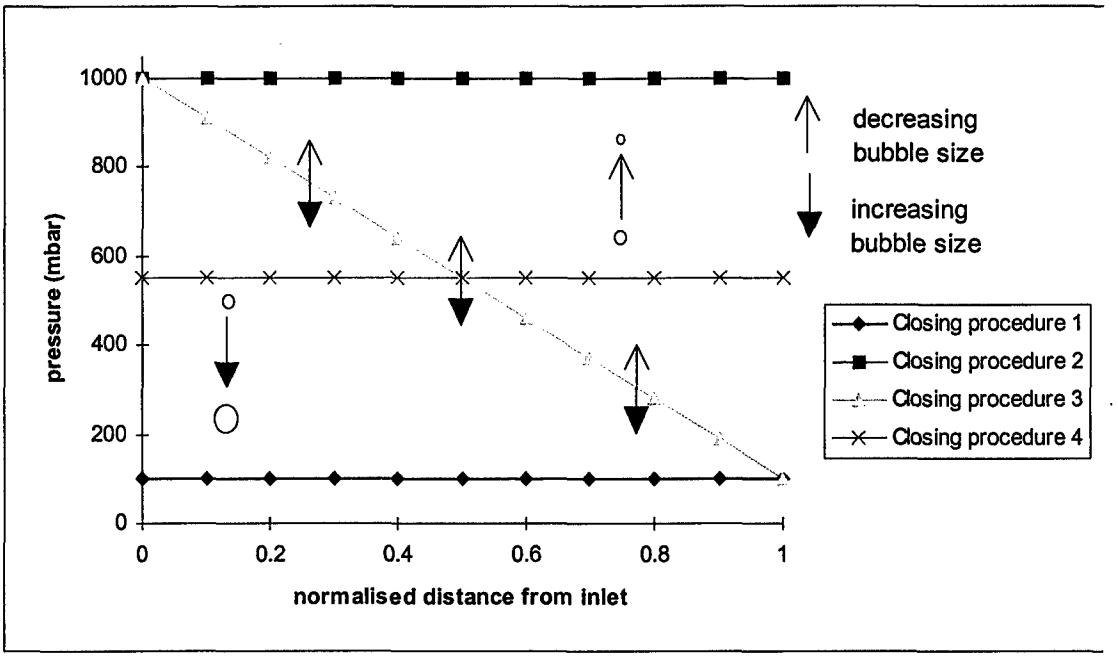

Figure 14: Pressure gradients for four closing procedures

As is demonstrated in Figure 14, the resulting pressure gradient during curing has a large influence on the void content, but also on the fibre volume content. Pressure readings like the ones shown in Figure 8 will help determining the time required between closing the infusion and starting of the cure of the laminate to allow the pressure gradient to adjust to the new situation.

7 Conclusions and recommendations

This report has given an introduction into a low cost, high quality production method for composite material structures, named vacuum infusion. This production method is a form of Resin Transfer Moulding, where the dry fibres are placed in a close mould and the resin is forced through the fibres by the pressure difference. The characteristics of the vacuum infusion process are described and the problems related to the applied flexible foil to close the mould. A short overview is given of recent vacuum infusion research programs, which focused on the theoretical modelling of the resin flow.

Much research remains to be done on the subject of vacuum infusion. A large part of this research should be based on experiments designed to obtain a better understanding of all the factors that play a part in the process. This report has presented several issues, which require attention. To facilitate the experimental research, a test set-up has been developed, which monitors the pressure development, the compaction (or relaxation) of the fibre mat, and the flowfront position.

This report illustrates the functioning of the test set-up and provides some resin flow characteristics for vacuum infusion. With regard to the test set-up, the results show that accurate pressure measurements and a continuous overview of the pressure development during injection are possible. The same is true for the deformation measurements with the displacement transducers. Combining the measurements with flowfront position data, gives an accurate pressure or displacement distribution against the distance travelled by the flowfront, from which pressure gradients can be derived.

The pressure and deformation measurements indicate a behaviour, which differs from other RTM processes carried out with two solid mould halves. As expected, the deformation of the flexible foil has its influence on the permeability, and subsequently on the pressure distribution over the mould. This behaviour makes prediction of the resin flow and filling times more difficult. However, the results show that the pressure distributions are equal, once the lengths of the moulds are normalised. From this result, the conclusion can be drawn that for given materials (fibres and resin) and pressure difference over the mould, the pressure distribution is a given property. Once this distribution is known, the resin flow can be predicted accurately. The pressure distribution results could also be used to model the flow theoretically and subsequently incorporate these relations in resin flow software. It is therefore not necessary to derive a correction term to Darcy's Law (as was originally foreseen in the research proposal) but to use the test data to predict the pressure gradient (as described above) and model this pressure gradient in the flow simulation.

The test set-up will also be very useful to investigate the different options for closing an infusion experiment. It will help determining the time required between closing the infusion and starting of the cure of the laminate to allow the pressure gradient to adjust to the new situation.

The authors intend to continue the research when new funds become available. More data will then be generated for commonly used reinforcement materials. Also the influence on the pressure gradient of the use of flow enhancement material, which is common practice during vacuum infusion, will be investigated The results will be published in relevant journals and magazines and presented at SAMPE and ICCM

conferences. These results will allow for more accurate flow simulations and fill-time predictions which is particularly advantageous for manufacturers of large and complex products like ships, wind turbine blades or aircraft wing or fuselage structures.

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